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THE INFLUENCE OF EXCITATION ON LIGHTNING SURGES IN TRANSFORMER --ETC(U)  
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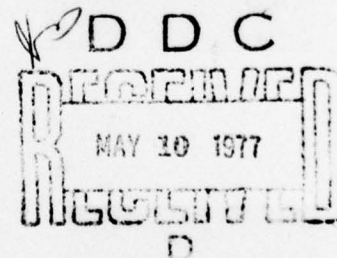
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THE INFLUENCE OF EXCITATION ON LIGHTNING SURGES IN  
TRANSFORMER COILS

by

A. Ketner



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## EDITED TRANSLATION

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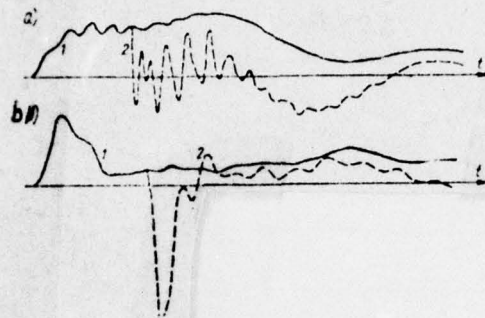
**THE INFLUENCE OF EXCITATION ON LIGHTNING SURGES IN TRANSFORMER COILS**

From "Electrical Engineering Review" 11/1975

**1. Introduction**

Lightning stroke tests used for testing the insulation of a transformer before it is put into operation are carried out on nonexcited objects. The test entails submitting the winding terminals to full and cut-off strokes. They pose a threat in a varying manner to the main and longitudinal windings. The main insulation is mainly endangered by the full stroke, while the longitudinal winding, depending on the construction of the winding, is endangered by either the full stroke or the cut-off one. Figure 1 shows the oscillograms





**Fig. 1. Typical oscillograms of lightning surges in channels caused by full and cut-off strokes for two varying winding constructions: a) stranded; b) continuous. 1 - full stroke; 2 - cut-off stroke.**

of surges in the channels caused by the full and cut-off strokes for two different winding constructions: a stranded winding and a continuous winding. The oscillograms of surges in channels shown in Fig. 1 were recorded with the same peak value of the cut-off and full stroke.

The strokes caused by the cut-off stroke in the longitudinal insulation of the stranded windings are less dangerous than those arising from a full stroke [1, 2], even when the peak value of the cut-off stroke is 15 greater than the full stroke. However in continuous windings the situation is different: the cut-off stroke presents a greater threat to the longitudinal insulation than the full stroke (Fig. 1b), even with the same peak values.

Surges caused by a lightning stroke superimpose themselves on the alternating working voltage. Their superposition can lead to greater stresses in the insulation system than those caused by the lightning stroke itself. The greater peak value of the working cut-off stroke than the full one anticipated in the norms (in Poland by 15 [10]) was justifiable by the possibility of the unfavorable superposition of stresses from the stroke and the working voltage. This view has been questioned [7, 8].

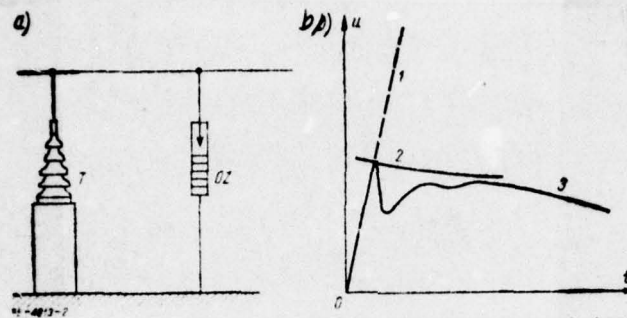
The present work, based on the publication of Lizunov and

Sapoznikov [9] presents an approximate analysis of the influence of excitation in the transformer on danger to the insulation with lightning strokes.

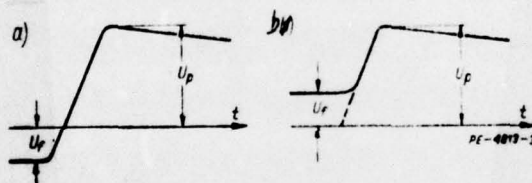
## 2. The Influence of Alternating Voltage on Danger Caused by a Full Stroke

Lightning arresters are the means of protecting the insulation of the transformer from surges (atmospheric and switching). They are connected between the conductors and the ground and hence, parallel to the protective insulation (Fig. 2). The peak value of the lightning voltages in the conductor in relation to the ground and therefore in the line terminal of the protective transformer is imposed by the characteristics of the lightning arrester: by the lightning-stroke characteristic causing the ignition voltage of the lightning arrester and the voltage-current characteristic determining its reduced voltage. The instantaneous value of the alternating voltage does not influence the peak value.

Figure 3 shows a change in the voltage on the line terminal. The value of the working voltage at the point of time considered (several  $\mu$ s) can be considered constant.



**Fig. 2. Protecting the insulation of the transformer from surges: a) system diagram; b) voltage flows. T - protective transformer; OZ - valve lightning arrester; 1 - incident stroke; 2 - characteristic of the lightning arrester; 3 - passed-through stroke.**



**Fig. 3. Change in the potential on the line terminal of the transformer excited by the application of a full stroke for opposite (a) and coincident (b) polarities of the stroke and the alternating voltage.  $U_p$  - peak value of stroke,  $U_r$  - instantaneous value of alternating voltage.**



Let us examine a uniform winding with a grounded star terminal after a rectangular voltage has been applied to its line terminal. The initial distribution of the lightning voltage along the winding with excitation of the transformer taken into consideration is determined by the following equation [8]:

$$(1a) \quad U_{ow}(x) = (U_p \pm U_f) \frac{\operatorname{sh} \left[ a \left( 1 - \frac{x}{l} \right) \right]}{\operatorname{sh} a} + U_f \left( 1 - \frac{x}{l} \right)$$

while for an unexcited transformer ( $U_f = 0$ ) [4]

$$(1b) \quad U_o(x) = U_p \frac{\operatorname{sh} \left[ a \left( 1 - \frac{x}{l} \right) \right]}{\operatorname{sh} a}$$

here  $U_p$  - peak value of the stroke;  $U_f$  - instantaneous value of the alternating voltage;  $a = 1/C, K$ ;  $K$  C and  $K$  capacitance to ground and longitudinal capacitance of the winding respectively;  $x$  - the length of the winding point from the line terminal;  $l$  - length of the winding.

The curve of the maximum to-ground surges along the winding can be described by using the method of "the vibrating wire" [3, 5] using the following equations:

- for the excited transformer [9]

(2a)

$$U_{mw}(x) = (2U_p \pm U_f) \left(1 - \frac{x}{l}\right) - \frac{(U_p \pm U_f) \operatorname{sh} \left[ a \left(1 - \frac{x}{l}\right) \right]}{\operatorname{sh} a}$$

- for the unexcited transformer ( $U_f = 0$ )

(2b)

$$U_m(x) = U_p \left[ 2 \left(1 - \frac{x}{l}\right) - \frac{\operatorname{sh} \left[ a \left(1 - \frac{x}{l}\right) \right]}{\operatorname{sh} a} \right]$$

In equations (1) and (2) the signs above refer to opposite polarities and those below to coincident polarities of the stroke and the alternating voltage. Figure 2 shows the voltage distribution (alternating, initial lightning voltage, and the curves of the maximum lightning strokes) along a uniform winding with a grounded star terminal. Next we will consider a more dangerous case - that of opposite polarity of the full stroke and alternating voltage, selecting the most useful moment (when the amplitude of the alternating voltage is the greatest and equal to  $U_{fmax}$ ). In this case, as contrasted with the unexcited transformer, we will obtain the following dependences of relations [9]:

- for curves of maximum to-ground surges

$$(3) \quad k_g = 1 + \frac{U_{f \max}}{U_p} \frac{\left(1 - \frac{x}{l}\right) sh a - sh \left[a \left(1 - \frac{x}{l}\right)\right]}{2 \left(1 - \frac{x}{l}\right) sh a - sh \left[a \left(1 - \frac{x}{l}\right)\right]}$$

- and for maximum gradients of the initial lightning voltage\* [\*]

[FOOTNOTE: By gradient  $g$  of the initial lightning voltage  $U_0(x)$  is understood derivative  $g = - \frac{dU_0(x)}{dx}$ . END FOOTNOTE].

$$(4) \quad k_{wp} = 1 + \frac{U_{f \max}}{U_p} \left(1 - \frac{th a}{a}\right)$$

Coefficient  $k_g$  represents the influence of excitation of the transformer on the values of the to-ground surges from a full stroke at various points of the winding (main insulation);  $k_{wp}$  is the influence on the maximum gradients of the initial lightning voltage (longitudinal insulation). From dependence (3) it follows that:

- at the line terminal, where strength is often the smallest, excitation has no influence on the value of the to-ground surges, and hence the existence of excitation does not change the danger;

- the greatest influence of excitation

$$k_{g \max} = 1 + \frac{U_{f \max}}{U_p} \frac{1 - \frac{a}{sh a}}{2 - \frac{a}{sh a}}$$

appears on the end of the winding (with a star terminal) where surges are small and do not determine dimensions of the main insulation;

- the influence of excitation as you move away from the line terminal is greater and greater; this influence becomes greater as coefficient  $a$  becomes greater.

The greatest values of to-ground surges for an excited and unexcited transformer occur at different, but nearby points of the winding - that is:

- for the excited transformer:

(5a)

$$\frac{x_m}{l} = 1 - \frac{1}{a} \operatorname{arch} \left( \frac{2 + \frac{U_{f \max}}{U_p} \frac{a}{sh a}}{1 + \frac{U_{f \max}}{U_p} \frac{a}{sh a}} \right)$$

- for the unexcited transformer



(5b)

$$\frac{x_m''}{l} = 1 - \frac{1}{a} \operatorname{arch} \left( 2 \frac{sh a}{a} \right)$$

The greatest dangers of cracking occur deep within the winding, and hence in a field basically uniform. Comparison of dangers of cracking in this part of the winding where a uniform field occurs with and without excitation makes it possible to evaluate the particular influence of excitation on lightning surges in the main insulation.

Coefficient  $k_{gmax}^*$ , which represents the influence of excitation of the transformer on the greatest value of the to-ground lightning surges, and hence on dangers of cracking, can be described by the dependence:

$$(3a) \quad k_{gmax}^* \approx 1 + \frac{U_{fmax}}{U_p} \frac{\left(1 - \frac{x_m'}{l}\right) sh a - sh \left[ a \left(1 - \frac{x_m'}{l}\right) \right]}{2 \left(1 - \frac{x_m''}{l}\right) sh a - sh \left[ a \left(1 - \frac{x_m''}{l}\right) \right]}$$

For voltages accepted in Poland for test oil-immersed transformers [10] one obtains, with nominal voltages of the windings

$U_n \geq 60$  kV the following values of ratio  $\frac{U_{fmax}}{U_p}$ :

- for transformers with a non-reduced level of insulation

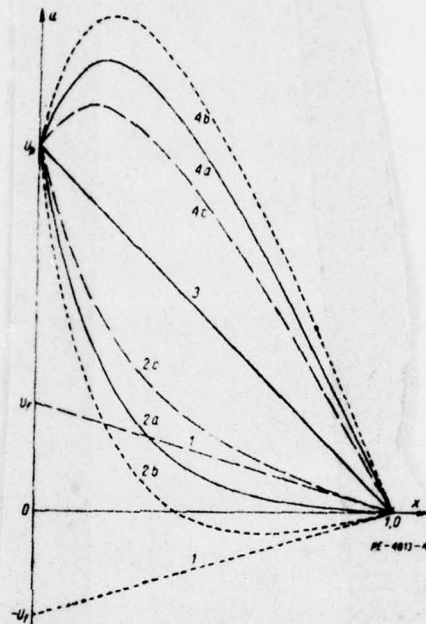


Fig. 4. Distribution of voltages along the winding with a grounded star terminal. 1 - alternating voltage before the application of stroke  $U_f(x)$ ; 2 - initial lightning voltages, (a - without excitation  $U_o(x)$ ; b, c - with excitation (with opposite and coincident polarities of the stroke and alternating voltage respectively) -  $U_{o10}(x)$ ; 3 - final arrangement  $U_k(x)$ ; 4 - curve of to-ground surges: (a without excitation  $U_m(x)$ ; b, c - with excitation (with opposite and coincident polarities of the stroke and the alternating voltage,  $U_{m10}(x)$ ).

0.18...0.19;

- for transformers with a reduced level of insulation

in stage I 0.22;

in stage II 0.24.

Figure 5 shows the graphs of the coefficients  $k_{gmax}$  and  $k_{up}$  calculated by using equations (3a) and (4) for limiting values in the ratio  $U_{fmax}/U_p = 0.18...0.24$  as a function of coefficient  $\alpha$ ; they illustrate the increase in danger to the main and longitudinal insulation with a full lightning stroke as a result of the existence of excitation.

Coefficient  $\alpha$  depends on the power, the nominal voltage, and the construction of the transformer windings; ratio  $U_{fmax}/U_p$  depends on the level of the test voltage (line parameters). Figure 6 shows the graphs of coefficients  $k_{gmax}$  and  $k_{up}$ , and also their ratio  $k_{up}/k_{gmax}$  as a function of coefficient  $\alpha$ , and here, depending on their power and voltage the following three groups are distinguished:

A - high-power transformers with upper nominal voltages  $U_n \geq 220$  kV ( $n \leq 7$ ) with a reduced level of insulation in stage II;

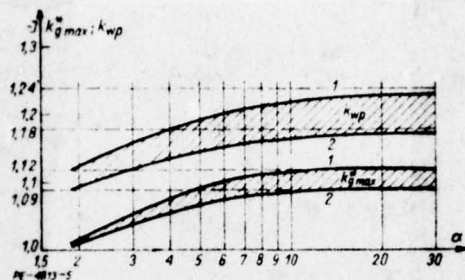


Fig. 5. The influence of excitation of the transformer on the increase of maximum lightning surges in the main insulation ( $k_{g \max}^*$ ) and the longitudinal insulation ( $k_{wp}$ ) for the full stroke as a function of coefficient  $\alpha$  for varying parameters. Curve 1 -  $U_{\max}/U_p = 0.34$ ; curve 2 -  $U_{\max}/U_p = 0.18$

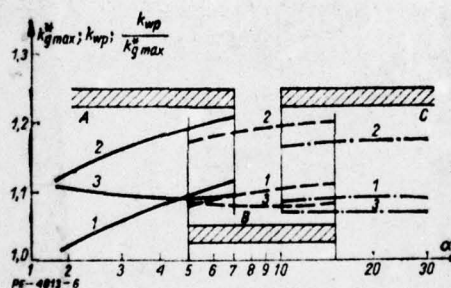


Fig. 6. The influence of excitation of the transformer on the increase of maximum lightning surges in the main and longitudinal insulation, and also their relationship for a full stroke in transformers of groups A, B, and C. Curve 1 -  $k_{g \max}^*$ ; curve 2 -  $k_{wp}$ ; curve 3 -  $k_{wp}/k_{g \max}^*$



B - high-power transformers ( $5 \leq \alpha \leq 15$ ) with voltages  $110 \text{ kV} \leq U_n \leq 220 \text{ kV}$  and with a reduced level of insulation in stage I;

C - high and medium-power transformers ( $\alpha \geq 10$ ) with voltages  $110 \text{ kV} \leq U_n \leq 220 \text{ kV}$  with a non-reduced level of insulation.

The influence of coefficient  $\alpha$  on the increase of dangers with a full stroke in the main and longitudinal insulation by virtue of the existence of excitation (Fig. 6) is most apparent in transformers belonging to group A and least apparent in transformers of group C. The limiting values of these coefficients are respectively:

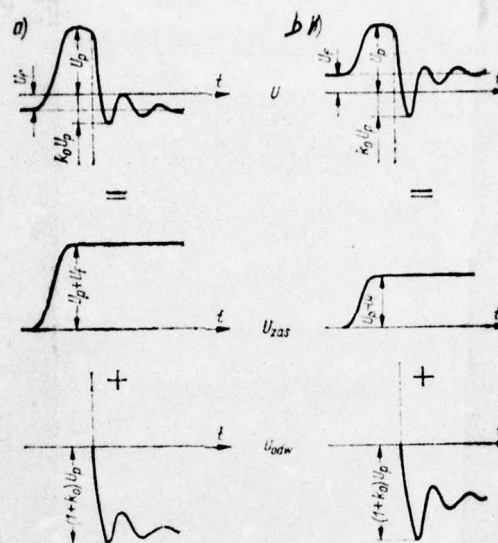
$k_{g\max} = 1.09 \dots 1.10$ ;  $k_{wp} = 1.18 \dots 1.20$  For all intents and purposes they do not depend on the transformers belonging to one of the enumerated groups; it is the result of the favorable set of parameters of the winding ( $\alpha$ ) and the network (level of test voltages  $U_{f\max}/U_p$ ). For all intents and purposes ratio  $k_{wp}/k_{g\max}$  does not depend on coefficient  $\alpha$  and is, depending on the level of the test voltages,  $1.07 \dots 1.11$ ; the value of this ratio increases insignificantly with a decrease in the level of the test voltages.

### 3. The Influence of Alternating Voltage on Dangers Caused by a Cut-Off Lightning Surge

Figure 7 shows the change in potential on the line terminal of the winding of a transformer excited by a cut-off stroke being applied to it with opposite and coincident polarities of the stroke and the working voltage. The peak value of the cut-off stroke, like the full stroke, does not depend on the instantaneous value of the working voltage; rather, it is imposed by the characteristics of the lightning arrester. The course of the voltage after cutting off the stroke, in the vicinity of the transformer's line terminal, is caused by a factor independent of it, which determines only parameters  $R$ ,  $L$ ,  $C$  of "the cut-off loop". The influence of excitation appears in such a way that oscillations after the cut-off die out, with the potential of the terminal being caused by the instantaneous value of the alternating voltage.

The influence of excitation of the transformer on dangers to the longitudinal insulation, caused by a cut-off lightning stroke, will also be considered in those windings in which they are larger than those caused by a full stroke. The analysis will mainly entail continuous, coil windings in which the oscillation amplitude of the stroke from the stroke being cut off ( $U_{umax}$ ) is in the majority of channels greater than the front of the surge ( $U_{cmax}$ );  $U_{umax} > U_{cmax}$ .

In an excited transformer lightning strokes on the longitudinal insulation caused by a cut-off surge can be considered as the



**Fig. 7.** Change in potential on the line terminal of the transformer of excitation  $U$  after the application of a cut-off stroke with opposite (a) and coincident (b) polarities of the stroke and the alternating voltage, and the resolution of this potential into two full strokes - a primary one ( $U_{pas}$ ) and a reverse one ( $U_{odw}$ )

superposition of surges on this insulation that are caused by two full strokes - a "primary" one and a "reverse" one - when there is no excitation (Fig. 7), as was done in works [3, 4], by considering the effects of applying a cut-off stroke to an unexcited winding. The peak value of the "primary" stroke  $(U_p + U_r)$  depends on the polarity of the stroke and the instantaneous value of the alternating voltage; however, the peak value of the "reverse" stroke  $(1 + k_0)U_p - w$  does not depend at all on excitation of the transformer.

Since surges on the longitudinal insulation are the superposition of surges caused by "primary" and "reverse" strokes they are influenced not only by the parameters of the winding, the time of the cut-off, the steepness of the front and the cut-off, but also by the peak values of both the component strokes; hence, the potential of the winding terminal in relation to the ground is also caused by the excitation of the transformer.

The analysis of surges in the channels of continuous coil windings leads to the following statements [4, 5]:

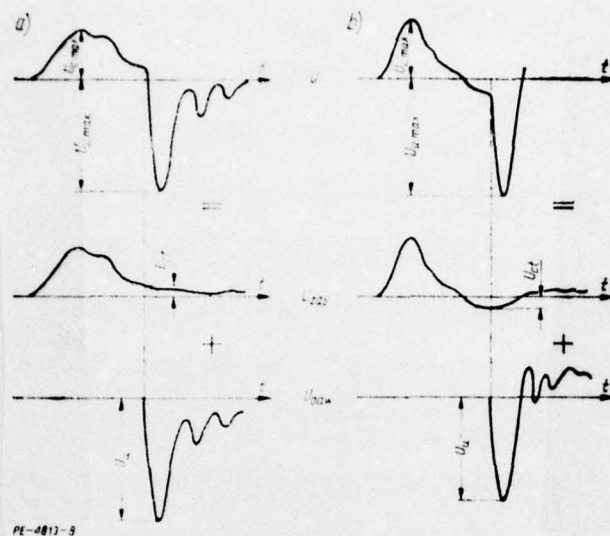
- in the flow of the voltage caused by the front of the stroke it is possible to distinguish a main surge (oscillation with a characteristic shape close to being triangular) that dominates irregular oscillations with amplitudes significantly smaller than the



peak value of the main surge;

- the time that the main surge lasts increases as it moves away from the line terminal; usually it is within the range of 1...5  $\mu$ s, while the length of time of the oscillations caused by the front of the stroke is of the order of several hundred  $\mu$ s. Personal measurements that were carried out on a significant number of coil windings of transformers of varying power and voltage confirm these observations;
- the time of the increase of the main surge fluctuates within the range 0.3...2  $\mu$ s.

The time of the cut-off (with time prior to the cut-off within the range of 2...3  $\mu$ s) [10] occurs on the descending (before or after passing through zero) part of the main surge in the channel caused by the front of the stroke, independent of the place in the winding. The real value of the main surge which is caused by the cutting off of the stroke at the terminal of the excited transformer will be the difference or the sum of the instantaneous values of the surge caused by the "primary" stroke, and the main surge caused only by the "reverse" stroke, according to whether the moment of the cut-off of the stroke occurs before or after a change in sign of the main surge from the "primary stroke (Fig. 8). The first case is less useful when the polarity of the stroke and the alternating voltage is coincident



**Fig. 8. Surge in channel U with a cut-off stroke and the resolution of this surge into components of two strokes: a primary one ( $U_{2as}$ ) and a reverse one ( $U_{od}$ ) for the moment of the cutting off occurring before the passage (a) and after the passage through zero (b) of the oscillation caused by the front of the stroke.**

(smaller value of the amplitude of the surge at the moment of cutting off from the "primary" stroke as compared with the same amplitude from the "reverse" stroke); the second case is less useful when the polarity of the stroke and the alternating voltage is opposite (greater value of the amplitude of the stroke at the moment of cut-off from the "primary" stroke as compared with the same amplitude from the "reverse" stroke).

For both cases and the least useful moment (the greatest amplitude of the alternating voltage -  $U_{fmax}$ ) dependence (6) is obtained, which designates the ratio of the amplitudes of the surges in the longitudinal insulation (in the channel) for an excited and unexcited transformer; its derivation is given in the supplement:

(6)

$$k_{wu} = 1 - \frac{U_{fmax}}{U_p} \frac{U_{ct}}{U_{cmax}} \frac{U_{cmax}}{U_{umax}}$$

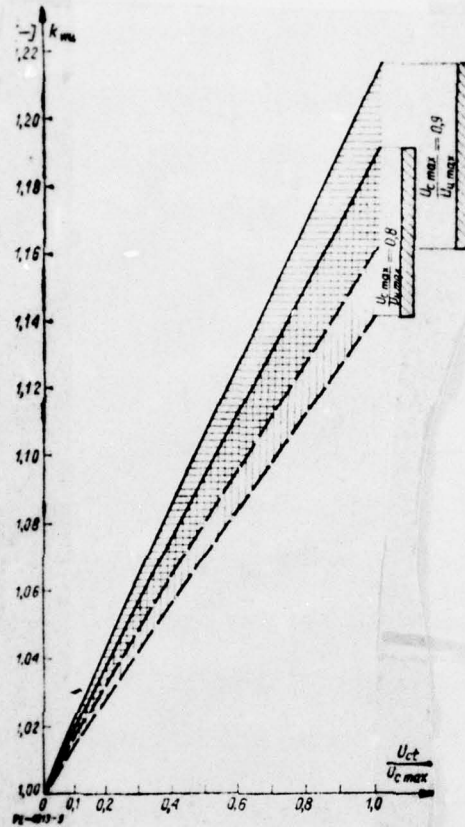
Coefficient  $k_{wu}$  represents the influence of excitation of the transformer on the values of surges in the longitudinal isolation for a cut-off stroke.

The value of coefficient  $k_{wu}$  mainly depends on the ratio of the instantaneous value of the voltage in the channel from the front of the stroke at the moment of cutting off to the maximum value  $U_{ct}/U_{cmax}$  and on the ratio of the maximum surge value in the channel caused by

the front and the stroke cut-off  $U_{\text{cmax}}/U_{\text{umax}}$ . The first ratio depends mainly on the time of cut-off; the second one, however, depends on the amplitude of the stroke oscillation after cut-off and on the steepness of the front and the stroke cut-off. In certain cases the value of ratio  $U_{\text{et}}/U_{\text{cmax}}$  can vary quite significantly, while the value of ratio  $U_{\text{cmax}}/U_{\text{umax}}$  does not vary a great deal. This makes it possible to consider it as a parameter (Fig. 9).

Ratio  $U_{\text{et}}/U_{\text{cmax}}$  changes along the winding. These changes depend on the speed of the penetration of the gradient wave in the winding. The oscillograms in Fig. 10 illustrate the nature of the changes of this ratio. They were recorded when investigating the arrangement of lightning surges in the continuous windings of two transformers - 240 MVA, 123 kV and 10 MVA, 110 kV. In one transformer (240 MVA, 123 kV) the moment of the stroke cut-off occurs after a change in the sign of the curve of the surge caused by the front of the stroke; in the second (10 MVA, 110 kV), before passage through the 0 axis. In the first case the value of ratio  $U_{\text{et}}/U_{\text{cmax}}$  changes insignificantly (decreases), but it increases in the second case. The graphs in Fig. 11, worked out on the basis of the oscillograms from Fig. 10 and dependence (6), illustrate changes in coefficient  $k_{\text{wu}}$  along the windings of the mentioned transformers, taking into consideration the most unprofitable cases. For input channels in both the analyzed transformers the value of coefficient  $k_{\text{wu}}$  is about 1.02, while in





**Fig. 9. Influence of excitation of the transformer on the increase in surges in the longitudinal insulation for a cut-off stroke as a function of ratio  $U_{ct}/U_{cmax}$  for varying parameters of ratio  $U_{cmax}/U_{umax}$  and  $U_{fmax}/U_p$ . Continuous line  $U_{fmax}/U_p = 0.24$ ; broken line  $U_{fmax}/U_p = 0.18$ .**

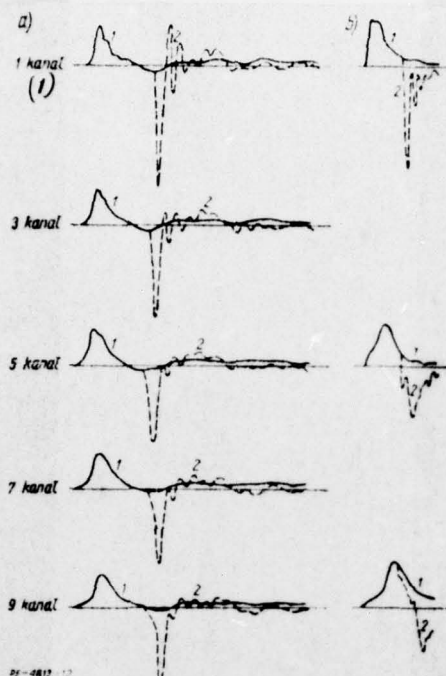


Fig. 10. Oscillograms of lightning surges in channels in the transformer windings: a) 120 MVA, 123 kV - time base 10  $\mu$ s; b) 10 MVA, 110 kV - time base 5  $\mu$ s. 1 - full stroke; 2 - cut-off stroke.

Key: (1) Channel.

more removed channels for one of the windings it changes little, but for the other one it increases, obtaining a value of 1.27 for the ninth channel from the line terminal.

In the first intercoil channel lightning surges from the cut-off stroke without excitation of the transformer reach significant values: 50 of the peak value of the stroke and sometimes even more. The values of these surges in more removed channels of the winding rather quickly decrease; for channels situated in the center part of the winding they stay on a level of about half the value of the surge in the first channel. Surge considerations then determine the dimensions of the longitudinal coiled insulation (of channels) at the beginning of the winding; but in the depth of the winding, as a rule other factors are determining (cooling) [6]. Figure 12 shows the arrangement of lightning surges for a cut-off stroke in the continuous winding of the above-mentioned transformers - 240 MVA, 123 kV and 10 MVA, 110 kV - with and without excitation, taking the most unfavorable cases (polarity, moment of the alternating voltage). It is clear from the graphs that the increase in lightning surges from the cut-off stroke by virtue of excitation in the input channels of the windings of the considered transformers, in which the danger of breakdown is great, is insignificant (several percent); yet, in the channels situated deep in the winding where dangers are small it can be, depending on the parameters of the insulation, a dozen percent or

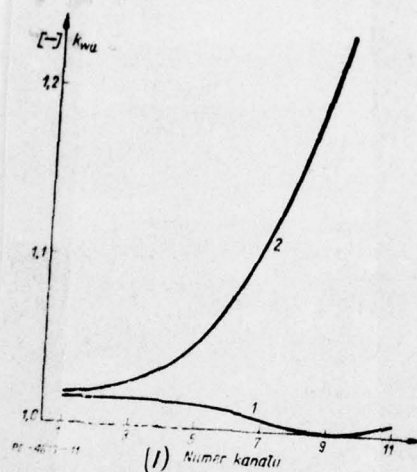


Fig. 11. Increase in surges for the cut-off stroke in the longitudinal insulation by virtue of excitation in the transformer windings: 1) 240 MVA, 123 kV; 2) 10 MVA, 110 kV.

Key: (1) Number of channels.

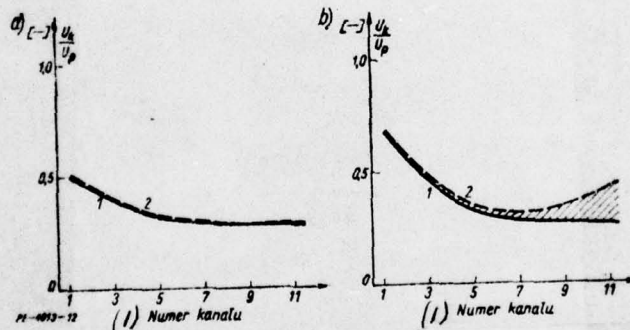


Fig. 12. Surges in channels of transformer windings: a) 240 MVA, 123 kV; b) 10 MVA, 110 kV. 1 - without excitation; 2 - with excitation.

Key: (1) Number of channels.



more to several tens percent

Dangers from the cut-off stroke when there is no excitation are, however, deep in the winding, so small that usually other factors (cooling) determine the dimensions of the longitudinal insulation of this part of the winding. Hence, the mentioned increase in the influence of excitation on surges in the central part of the winding has no practical meaning.

#### Conclusions

An approximate evaluation of lightning surges in an excited transformer allow the following statements to be made:

A more unfavorable influence of the superposition of stresses arising from a lightning stroke and the working alternating voltage for a full stroke occurs with opposite polarities; while for a cut-off stroke, depending on the parameters of the winding and the stroke, it can occur with both coincident and opposite polarities of the stroke and the working alternating voltage.

The increase in stresses in the main and longitudinal insulation from the full stroke in an excited transformer (a more dangerous case

and the least profitable moment), in comparison with an unexcited transformer, is dependent on coefficient  $\alpha$ . The limiting values of the coefficients for an increase in dangers, depending on the power and voltage of the transformer and the level of test voltages are:

in the main insulation - 1.09...1.10

in the longitudinal insulation - 1.18...1.20.

Increase in stresses with a full stroke caused by the existence of excitation is, for the longitudinal insulation, 7-11% greater than that for the main insulation.

The increase in stresses caused by excitation of the transformer in the most threatened input channels is insignificant with a cut-off stroke. For the most unfavorable case it can amount to about 4%. However in channels located deep within the winding the increase can be greater (20-30%). That is not however a true practical value since safety margins of the channels in this part of the winding are usually excessive, a fact arising from their dimensions determined by thermal considerations.

The influence of excitation of the transformer with cut-off strokes is dependent on many factors, the parameters of the winding

and the cut-off stroke playing the most important role. In many cases this influence for all intents and purposes can be neglected.

The influence of excitation of the transformer on stresses in the insulation system must be taken into account when setting the coordination margin between the level of protection and the test voltage by the full stroke; it however does not justify increasing the peak value of the cut-off stroke as compared with the full one.

#### Supplement - Derivation of Dependence (6)

To derive dependence (6) we will use Fig. 8 which shows surges with a cut-off stroke as the superposition of surges caused by two full strokes: a principle one and a reverse one [5]. The value of the surge caused by cutting off the stroke, depending whether or not the moment of cut-off occurs before or after a change in sign of the oscillations caused by the front of the stroke, will be the difference or the sum of the amplitudes of the surges at the moment of cut-off, which are caused by the primary and reverse strokes. The first case (a) is less useful when the polarity of the stroke and the alternating current is coincident; in the second case (b) it is least useful when the polarity is opposite.



The ratio of the greatest amplitudes of the lightning surges in the channels in the excited transformer is for the most threatening cases the following:

$$k_{uu} = \frac{U \pm U_{ct}^*}{U \pm U_{ct}}$$

The designations of the amplitudes are in agreement with those given in Fig. 8, while the values referring to the excited transformer are designated by an asterisk - \*. The signs above refer to the first case (a), and those below to the second case (b).

Taking into account that  $U_{u\max} = U \mp U_{ct}$ , we obtain:

$$k_{uu} = \frac{U_{u\max} + (U_{ct} - U_{ct}^*)}{U_{u\max}}$$

and after transformation and simplification

$$k_{uu} = 1 \pm \frac{U_{ct} - U_{ct}^*}{U_{u\max}}$$

After multiplying and dividing the second term of the above expression by  $U_{c\max}$ , and then after transformation and taking into account that amplitude  $U_{ct}^*$  is proportional to the peak value of the primary stroke  $(U_p \mp U_{f\max})$ , and amplitude  $U_{ct}$  to  $U_p$ , we obtain dependence (6)

$$k_{uu} = 1 + \frac{U_{f\max}}{U_p} \frac{U_{ct}}{U_{c\max}} \frac{U_{c\max}}{U_{u\max}}$$

Coefficient  $k_{uu}$ , which accounts for the increase in stresses in



the longitudinal insulation of coil windings for a cut-off stroke by virtue of the existence of excitation also depends on the relationship:

- of the instantaneous value of the surge at the moment of cut-off and the maximum value caused by the front of the stroke (hence it depends on the time to the cut-off);

- of the largest amplitudes of the surges caused by the front and the cutting off of the stroke; therefore it also depends on the steepness of the front and the cut-off and on the amplitude of the voltage oscillation after the cut-off.

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